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Land conservation can mitigate freshwater ecosystem services degradation due to climate change in a semiarid catchment: The case of the Portneuf River catchment, Idaho, USA

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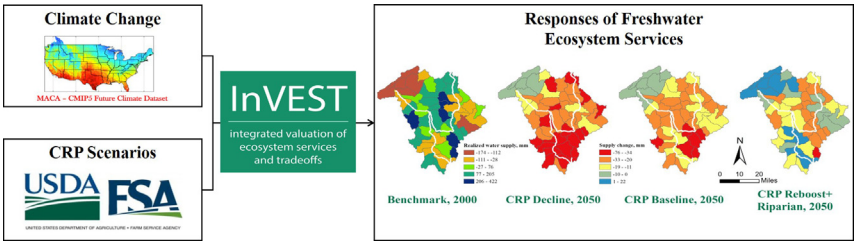
HIGHLIGHTS

- Freshwater ecosystem services (ES) under climate change and conservation assessed
- Degradation of freshwater ES is expected as a result of climate change.
- Increasing agricultural land conservation would offset the degradation.
- Model outputs are sensitive to the parameters of major land cover types.
- This study has potential implications for other semiarid catchments.

GRAPHICAL ABSTRACT



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ABSTRACT

There is increasing evidence of environmental change impacts on freshwater ecosystem services especially through land use and climate change. However, little is known about how land conservation could help mitigate adverse water-sustainability impacts. In this paper, we utilized the InVEST tool and the Residual Trends method to assess the joint effects and relative contributions of climate change and land conservation on freshwater ecosystem services in the Portneuf River catchment in Idaho, USA. We developed five hypothesized scenarios regarding gain and loss in the enrollment of Conservation Reserve Program (CRP), the largest agricultural land-retirement program in the U.S., plus riparian buffer and assessed their interactions with climate change. Results suggest that the realized water yield in the Portneuf River catchment would possibly be 56% less due to climate change and 24% less due to the decline of CRP enrollment. On the contrary, if CRP enrollment is promoted by ~30% and riparian buffer protection is implemented, the water supply reduction in the year 2050 could be changed from 56% to 26%, the total phosphorus (TP) and total nitrogen (TN) export would be reduced by 10% and 11%, and the total suspended sediment (TSS) reduced by 17%. This study suggests that increasing implementation of the CRP would likely preserve key freshwater ecosystem services and assist proactive mitigation, especially for semiarid regions vulnerable to changing climate conditions.

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1. Introduction

Freshwater ecosystems are responsible for the provision of a variety of services to humanity. The ecosystem services (ES) involve not only direct benefits to society, such as the supply of drinking water,

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hydropower, industrial and agricultural water usage, water purification, and erosion control, but also indirect impacts on human health, recreation and culture (De Groot et al., 2010; Keeler et al., 2012). The provisioning and functionality of freshwater ES are projected to be severely impacted by global climate change (Boithias et al., 2014; Brauman et al., 2007; Field et al., 2014; Foley et al., 2005; Pronk, 2002). Specifically, the impacts of climate change on semiarid regions are more evident given their climatological characteristics of low annual precipitation with high spatial variability, high potential evapotranspiration, and low annual runoff (Branson et al., 1981; Terrado et al., 2014). Current trends indicate that a warming climate will impact semiarid regions by concentrating the rainfall period during the year and causing more extended droughts (Brown et al., 2012).

Besides changing climate, anthropogenic changes, e.g., urbanization, population growth, and agriculture, are also major stressors for freshwater ES (Dodds et al., 2013; Foley et al., 2005; Zimmerman et al., 2008). In the anthropogenic changes, agricultural production is the largest consumer of freshwater. Land use change induced by agricultural intensification will likely increase water demand and lead to more pesticide and fertilizer use, and thus potentially cause water scarcity and deteriorate water quality (Boithias et al., 2014; Hamel et al., 2015; Secchi et al., 2011). To mitigate the possible negative impacts, solutions such as land conservation have been used to target the environmentally sensitive land and remove crops from production (Foley et al., 2011; Kovacs et al., 2013; Polasky et al., 2011). However, few empirical studies have either integrated land conservation with the two stressors of climate change and agriculture or explored the mitigating potential of agricultural land conservation practices under global change (Gleason et al., 2011; Johnson et al., 2016; Runting et al., 2017).

The Conservation Reserve Program (CRP) administered by the U.S. Department of Agriculture (USDA) has provided critical ES. Rooted in practices implemented in the 1950s and formalized in 1985, the CRP specifically targets the retirement of highly ecologically sensitive cropland and pasture to achieve water quality improvement (Johnson et al., 2016), wildlife habitat enhancement (Hiller et al., 2015), greenhouse gas emission reduction (Gelfand et al., 2011), soil erosion and nutrient load reduction (Gleason et al., 2011), and flood damage reduction (Todhunter and Rundquist, 2008). The CRP has an annual expenditure of about $2 billion and a long enrollment period from 10 to 15 years of contract for conserved land (Farm Service Agency, 2017; Stubbs, 2014). Even though the CRP provides more ES benefits than its rental payment (Hansen, 2007; Johnson et al., 2016), the program's cap, namely, the statutory limit of the maximum allowable acreage based on the Agricultural Act, has declined from its peak of 32 million acres in financial year (FY) 2007 to 24 million acres in FY2018 after the reauthorization of the Agricultural Act of 2014 (2014 farm bill hereafter, P.L. 113-79). The CRP enrollment has also declined from its peak of 36.8 million acres in 2007 to 23.4 million acres in 2017 due to the decreased cap, high commodity prices, and low rental rates (Chen and Khanna, 2014; Hellerstein, 2017; Newton, 2017; Stubbs, 2014). An additional 7.8 million acres on contracts will expire between 2018 and 2022 (Farm Service Agency, 2017). Thus, more research is needed to assess how the fluctuation and alternative scenarios of the CRP will affect freshwater ES in regions where the enrollment is evident.

In this study, we aim to comprehensively assess the relative contributions and joint effects of climate change and land conservation through CRP on freshwater ES in the Portneuf River catchment in Idaho, USA. The Portneuf River catchment is a semiarid basin troubled with water scarcity and water quality problems due largely to irrigation and fertilizer applications in agricultural production (Bechtold et al., 2012; Hopkins et al., 2011; IDEQ, 2010; Marcarelli et al., 2010; Minshall and Andrews, 1973). We used the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) tool to model the services of water supply, water purification, and sediment retention under different climate change and conservation scenarios (Sharp et al., 2014). We address the following questions: (a) If current land use and management practices persist, how will freshwater ES likely respond to climate change? (b) To what extent will land conservation, such as the CRP, help offset the adverse effects of climate change? (c) Given the spatially explicit results from InVEST, what are the implications for policy making to maintain current freshwater ES? We hypothesize that climate change and declining CRP enrollment will negatively affect the freshwater ES, whereas increasing CRP enrollment will partially offset the degradation and even counteract the impacts due to climate change.

2. Material and methods

2.1. Study area

The Portneuf River in southeastern Idaho, USA, is a fifth order river that drains 3500 km^2 (Fig. 1). The catchment is characterized by a semiarid climate with low annual precipitation, ranging from 330 mm at Pocatello city to 760 mm in the mountains (Minshall and Andrews, 1973), and high potential evapotranspiration, as large as 1550 mm in lower Portneuf valley (Welhan, 2006). The largest urbanized city in the region is Pocatello (population 54255 based on the 2010 census). Land use cover in the catchment is dominated by rangelands (60% of total area, with 41% as shrublands and 19% as grasslands; 28% is grazed), followed by croplands (14%), forest (13%), urban area (1%), and water (1%). About 8% of the catchment area is irrigated, and 85% of the irrigation withdrawal is from surface water (Marcarelli et al., 2010). The CRP land covers 11% of the catchment (NRCS, 2007). Among the three major counties in the catchment, Bannock County ranks 78th in terms of CRP enrollment, and Bingham County and Caribou County rank in the top 250 (118th and 245th) among 2511 participating counties in 2017 (Farm Service Agency, 2017).

The river is listed as ecologically impaired with respect to several of the criteria regulated under the federal Clean Water Act, including excess sediment and nutrients (N and P), as well as low flows and low dissolved oxygen in its downstream segments (IDEQ, 1999, 2010). The water consumption by irrigation accounts for 94.5% of the total consumptive use in the catchment (Solley et al., 1998). The consumptive use lowers discharge during summer by 70% compared to if the river were unregulated (Marcarelli et al., 2010). The catchment is also troubled with high concentrations of nitrogen, phosphorus, and turbidity from suspended sediments (Hopkins et al., 2011). The high nitrogen concentration and turbidity are mainly associated with agricultural practices and fertilizer application, whereas the high phosphorus concentration is related to the phosphorus processing complex located downstream of Pocatello (Baldwin et al., 2004). Marsh Creek is the largest tributary to the Portneuf River, which significantly contributes to the high nutrient and suspended sediment loads due largely to intensive agricultural activities within the drainage area (Layhee et al., 2015; Marcarelli et al., 2009). The river has its headwaters and outlet on the Fort Hall Reservation of the Shoshone-Bannock Tribes, adding additional jurisdictional complexity to and impetus for sustaining river-related ES.

2.2. Scenario building and modeling using InVEST

We modeled hypothesized scenarios to assess the joint and individual effects of climate change and CRP enrollment changes on freshwater services (Fig. 2). We used an InVEST model for each of our primary ES response variables: water yield, nutrient retention, and sediment retention (Appendix A). The InVEST tool is easily accessible and widely used in modeling ES change caused by climate and land use changes (Boithias et al., 2014; Fu et al., 2017; Hoyer and Chang, 2014; Pan et al., 2015). It is based on ecological production functions parameterized on land use management, aiming to cope with study area as large as a nation or as small as an individual catchment (Redhead et al., 2016; Sharps et al., 2017). It focuses on scenario comparisons via a first-order assessment rather than accurate prediction (Guswa et al., 2014; Hamel et al.,

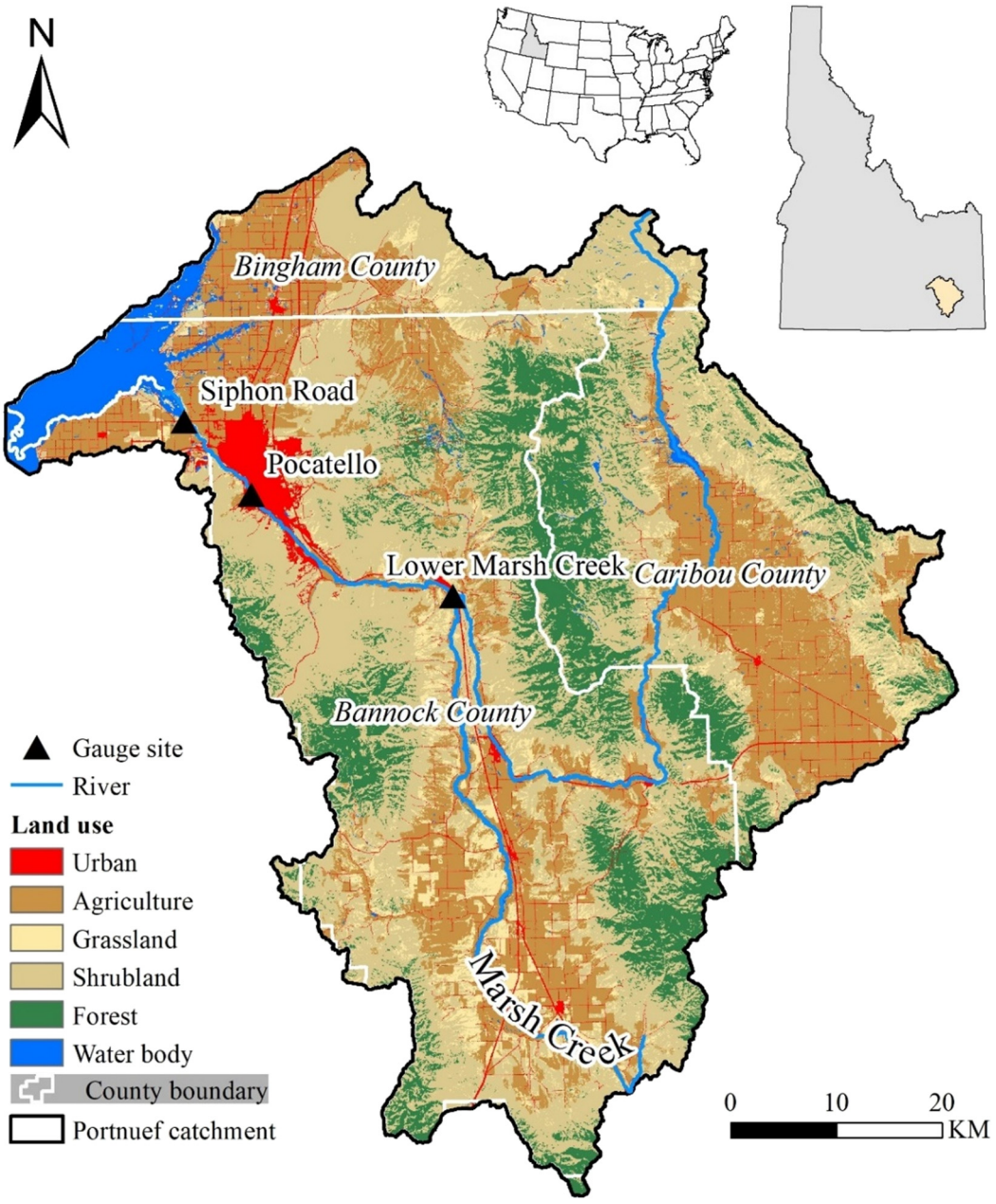

Fig. 1. Portneuf River catchment in southeastern Idaho.

2015). It also provides application program interface (API) that could be integrated into complicated workflows, by which we iterated the scenarios automatically (Sharp et al., 2014). The spatially explicit outputs generated by the InVEST tool can provide insights for decision making targeting environmentally sensitive regions for potential retirement from agricultural activities within the study area and beyond (Sharps et al., 2017; Vigerstol and Aukema, 2011). In the practices of InVEST modeling, the freshwater ES are estimated at the pixel level and aggregated to the subcatchment level at which the results are interpreted (Sharp et al., 2014).

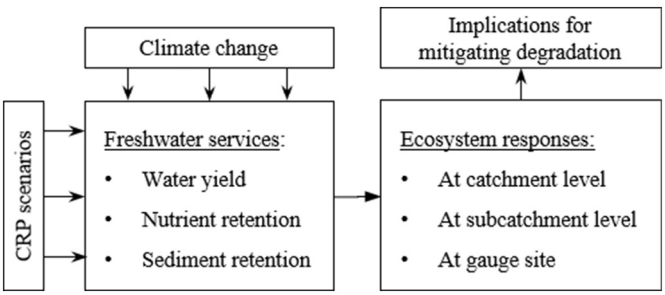

Fig. 2. Assessment framework.

For the climate change scenarios, we used downscaled climate data produced by the multivariate adaptive constructed analogs (MACA) method at 4 km resolution (Abatzoglou, 2013). The high greenhouse emission option, Representative Concentration Pathway (RCP) 8.5, was used because current trends are near the high end of emission scenarios (Peters et al., 2012; Snover et al., 2013). Though their simulation performance varies in the study area, all of the 20 climate models of Coupled Model Intercomparison Project Phase 5 (CMIP 5) in the MACA dataset were used with equal weight to provide as many as possible scenarios regarding the impacts of climate change (Mote et al., 2011; Rupp et al., 2013; Taylor et al., 2012) (Appendix A). The years 1986–2015 were used for the Benchmark scenario centered on 2000 and the years 2036–2065 for alternative scenarios centered on 2050

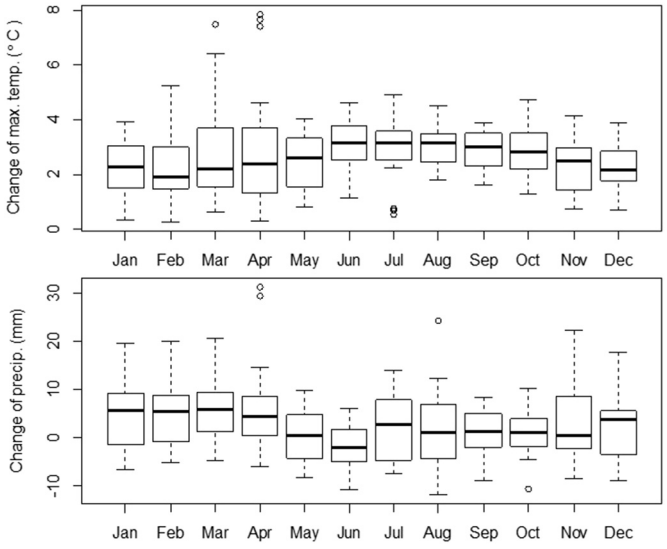

Fig. 3. Monthly change of precipitation and daily maximum air temperature from 2000 to 2050.

(Hoyer and Chang, 2014). The MACA data show that in the catchment the daily maximum air temperature will increase by 2.7 °C and the annual precipitation will increase by 35.2 mm from 2000 to 2050 (Fig. 3). We used multiple model inputs obtained from multiple sources (Table 1). In the model inputs, the reference evapotranspiration grid was calculated by the Modified-Hargreaves (MH) method largely because the MH method is robust in dealing with data with uncertainty and for arid regions (see Droogers and Allen, 2002).

We built alternative CRP scenarios in two steps. First, the historical CRP enrollment acres were estimated at the catchment level and the future changes were hypothesized. Statistics of the Bannock, Caribou, and Bingham counties were proportionally aggregated.[2] There are three phases in the historical CRP enrollment (Fig. 4). The enrollment in 2001 was used as the Benchmark scenario and various enrollment acres were assumed under the alternative scenarios in 2050 (Table 2). We assumed that in the "CRP Baseline" scenario, there is no enrollment change; in the "CRP Decline" scenario, the enrollment will decline by 29% compared with the Benchmark scenario; in the "CRP Loss" scenario, the enrollment will extremely decline by 60% of the Benchmark scenario; in the "CRP Reboost" scenario, the enrollment will increase by 29% in contrast to the "CRP Decline" scenario; and the "CRP Reboost +Riparian" scenario is the CRP Reboost scenario plus the riparian protection that converts land within 30 m of streams to grassland, providing additional 4195 acres (5% of current CRP enrollment) of land conserved along streams (Johnson et al., 2016; Santhi et al., 2014; Yasarer et al., 2016).

Second, the enrollment changes were applied as land use change by certain conversion rules (Fig. 5). We used the 2001 National Land Cover Database (NLCD) in the Benchmark scenario and generated the alternative scenarios by InVEST Scenario Generator tool (Sharp et al., 2014). Considering the cost to convert and manage new croplands, larger grassland patches were given priority to become croplands in the CRP Decline and CRP Loss scenarios. In the Reboost scenario, croplands near grassland were converted to improve the connectivity of existing conservation land. For the Reboost+Riparian scenario, croplands and urban areas within 30 m of streams were converted to grasslands to achieve riparian protection in addition to the CRP Reboost scenario (Gleason et al., 2011).

[2] $CRP_{pt} = \sum_{ct} CRP_{ct} \cdot (Area_{ct}^{pt}/Area_{ct})$, where CRP_{pt} is the enrollment acres in the Portneuf River catchment, CRP_{ct} is the enrollment acres reported at the county level (Farm Service Agency, 2017), $Area_{ct}^{pt}$ is the area that falls within the catchment for each county, and $Area_{ct}$ is the total area of each county.

We further employed the Residual Trends (RESTREND) method to quantify the proportion of climate change and conservation contributing to changes in freshwater ES (Wessels et al., 2007). The method hypothesizes two scenarios for which only one of the climate and land use change factors is altered and computes the ratio of the residual trend to the actual change (Pan et al., 2015):

$$\eta_d = \frac{W_s - W_{d'}}{W_s - W_b} \times 100\% \quad (1)$$

In the equation, η_d is the relative contribution of climate change or CRP trends as dimension d; W_s are the freshwater ES under the joint scenario s; W_b are the freshwater ES under the Benchmark scenario b; for $W_{d'}$, if d is climate change, $W_{d'}$ are the freshwater ES under the scenario d' with only land use change, and if d is CRP change, $W_{d'}$ are the freshwater ES under the scenario d' with only climate change.

2.3. Model calibration and uncertainty

The model parameters in InVEST were calibrated by comparing the outputs with the observation from multiple gauge sites along the Portneuf River (Fig. 1 and Table 3). Estimates of upstream subcatchments for each gauge site were summed and converted to annual flux of water, nutrients, and suspended sediment. Observation data were extracted from the downstream sites like the Siphon Road site and the Pocatello site to represent the overall responses for the catchment, except the Lower Marsh Creek site due to data availability. As shown in Table 3, the flow estimation shows no difference with the observation after calibration. The nutrient flux is underestimated by 2.1% for total phosphorus (TP) and 2.7% for total nitrogen (TN), while the sediment flux is overestimated by 1.4%. The source and the calibrated biophysical parameters associated with each LULC type are presented in Appendix B.

We estimated the uncertainty of the parameters from each InVEST model to provide evaluation means for the quality and credibility of the ES analysis and build trust with stakeholders (Hamel and Bryant, 2017). In the hydrological modeling, sensitivity analysis (SA), defined as the investigation of the response function that links the variation in the model outputs to the changes in the model inputs, is widely used to identify important factors and model uncertainty (Sánchez-Canales et al., 2012; Song et al., 2015). We used the enhanced Morris method, which is also called the Elementary Effects (EE) method in Saltelli et al. (2008) (Appendix A). The method was preferred rather than the original One Factor At a Time (OAT) method because the EE method is free of the additive assumption required for the model and explores the global sensitivity across the model's input space (Campolongo et al., 2007; Saltelli and Annoni, 2010).

3. Results

3.1. Water provisioning

The InVEST outputs of the water yield model suggest that climate change would likely reduce the current water supply by 56% (Table 4). The water yield would decline principally because evapotranspiration exceeds the precipitation increase due to higher air temperature. In contrast, the contribution of CRP depends on the scenario adopted, ranging from decreasing water yield by 47% in the CRP Loss scenario to increasing the supply by 30% in the CRP Reboost+Riparian scenario. The joint effects of climate change and CRP are represented by the total percentage change, which is the sum of the relative contributions. Almost 100% loss of water provisioning would possibly occur in the CRP Loss scenario because of the warming climate and the amount of conversion from CRP land to agricultural land. Compared with the CRP baseline scenario, the CRP Reboost scenario could counteract the reduction due to climate change by 23%, and the CRP Reboost+Riparian scenario would further increase the rate by 7% and enhance the mitigation effect to 30%. The

Table 1
Data requirements and sources for water yield modeling (WYM), nutrient retention modeling (NRM), and sediment retention modeling (SRM).

Data	Label	Model	Source	Description
Annual average precipitation	*Pr*	WYM; NRM	MACA	Spatial resolution at 4 km * 4 km
Reference evapotranspiration	*ETo*	WYM	MACA	Spatial resolution at 4 km * 4 km; calculated by the modified Hargreaves method (Droogers and Allen, 2002)
Soil depth	–	WYM	STATSGO	Minimum of restricting layer depth and root depth; converted to 500 m * 500 m raster
Plant available water content	*PAWC*	WYM	STATSGO	The fraction of water in soil that is available to plants; converted to 500 m * 500 m raster
Land use/land cover	*luc*	All	NLCD	Standard national land cover product; contains 15 land cover categories
Catchment polygons	–	All	NHD	The 8-digit and 12-digit catchment boundaries
Digital elevation model (DEM)	–	SRM; NRM	NED	Spatial resolution at 30 m
Rainfall erosivity	R_x	SRM	MACA	Erosion potential due to kinetic energy of rainfall; calculation following Nearing (2001) and Renard and Freimund (1994)
Soil erodibility	K_x	SRM	STATSGO	Soil's susceptibility to detachment and transport by rainfall
Water consumption coefficient	WC_x	WYM	National Water-Use Science Project	Calculated by authors (Solley et al., 1998)

mitigation effects are largely due to the reduction of the consumptive use in the catchment by more CRP enrollment. However, even with the greatest proposed conservation efforts under the CRP Reboost+Riparian scenario, the realized water yield would likely decrease by 26% because of climatic change (Table 4).

The mapping of the spatial variation of water supply at the subcatchment level, as shown in the Benchmark scenario in Fig. 6, indicates that mountainous areas in the central catchment are the major contributor to the water yield, functioning as a regional "water tower" (Viviroli et al., 2007). For future scenarios of water supply (Fig. 6 (a–i)), a consistent trend of improvement along the diagonal of the map matrix is observed. As the climate scenarios switch from an extreme warming and drier one (first quantile in the map) to a scenario with moderate increase in air temperature and precipitation (third quantile in the map) and the CRP scenarios move from enrollment reduction (the CRP Decline) to enrollment increase (the CRP Reboost+Riparian), fewer subcatchments would experience water scarcity. With declining CRP enrollment (Fig. 6 (a–c)), the subcatchments along Marsh Creek would possibly experience severe water scarcity within the next 50 years, reducing the water yield by 22 mm on average (Fig. 6 (b) minus (e)). In contrast, the areas with more CRP enrollment show positive changes (Fig. 6 (g–i)). The subcatchments along the Portneuf River and Marsh Creek might have the most improvement, with the increase of water supply ranging from 1 mm to 34.4 mm (Fig. 6 (h) minus (e)).

3.2. Water purification

The relative runoff potential index, $\lambda_x/\overline{\lambda_W}$, as the proportion of each pixel x in the total rainfall of the catchment, shows little change under climate change. The TP and TN export estimates are mostly influenced by the export coefficient of x (Eqs. (A.6) and (A7)). Therefore, land use and hypothesized CRP changes are likely to overwhelmingly determine the nutrient export change from 2000 to 2050 (Table 4). The CRP Decline and CRP Loss scenarios tend to degrade freshwater ES by introducing N and P fertilizer applications. On the other hand, the CRP Reboost scenario could reduce nutrient export by 7% and 8% for TP and TN export because fertilizer applications would be reduced and grassland cover has greater nutrient retention than cropland. In addition to the CRP Reboost scenario, the CRP Reboost+Riparian scenario is likely to further reduce TN and TP export by 3% because of riparian protection. TN appears slightly more sensitive than TP to land use changes because the TN export would increase by 16% in the CRP Loss scenario and decrease by 11% in the CRP Reboost+Riparian scenario, whereas TP export would increase by 11% and decrease by 10% under the two scenarios.

In our modeled scenarios, the geographic distribution of TP and TN export reveals that nutrient export is mostly attributed to croplands in the catchment (Figs. 7 and 8). In the Benchmark scenario, the areas south of the middle Portneuf River and along Marsh Creek substantially contribute to the nutrient export, which is due largely to the row crop agriculture in the region. The croplands to the northwest of the city of Pocatello would contribute less nutrients because the precipitation in the region is relatively low and thus the runoff index is small. The spatial pattern further confirms that TN and TP export is insensitive to climate change using the InVEST modeling approach. A substantial difference is identified among CRP scenarios, especially for the subcatchments along Marsh Creek. Under the CRP Decline scenario, TP export in the Marsh Creek subcatchments would increase by 13% and TN export would increase by 21%, likely due to the conversion of native grasslands by 52% in the region. However, the situation in the Marsh Creek subcatchments would be improved under the CRP Reboost+Riparian scenario, reducing TP by 16% and TN by 18%.

3.3. Erosion control

The response of TSS export is complex under changing climate and CRP scenarios (Table 4). As shown in the CRP Baseline scenario, climate change might lead to 11% more TSS export because of more precipitation and thus higher rainfall erosivity (Eq. (A.9)). Under the CRP Decline and CRP Loss scenarios, the contribution of climate change would be augmented to 14% and 16%, respectively, compared with its consistent contribution in the water yield and nutrient export results. The ~30%

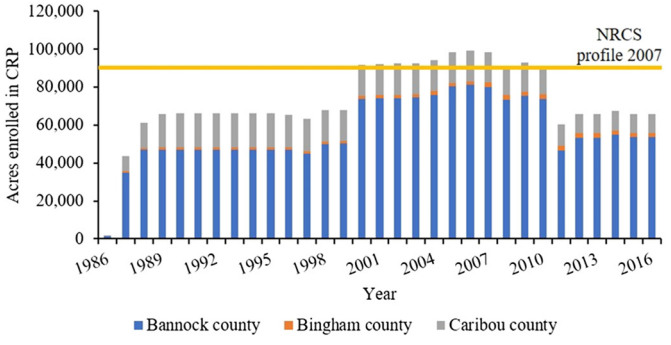

Fig. 4. Estimation of the CRP enrollment acres in the Portneuf River catchment. Note: As the only available report at the catchment level, the profile from Natural Resource Conservation Service (NRCS) in 2007 shows that our estimation is close to the reported value.

Table 2
Settings for climate change and conservation scenarios.

Scenario	Climate data	Enrollment acres
Benchmark	1986–2015	92,217
CRP Loss	2036–2065	38,261
CRP Decline	2036–2065	65,239
CRP Baseline	2036–2065	Same as Benchmark
CRP Reboost	2036–2065	118,700
CRP Reboost+Riparian	2036–2065	122,895

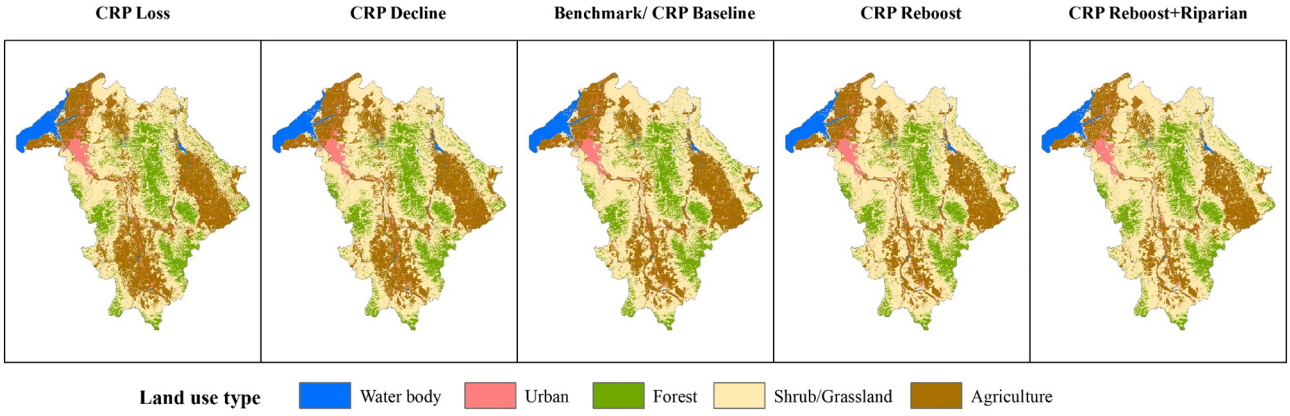

Fig. 5. Land use cover for CRP scenarios from declining (left) to increasing (right) enrollment.

Table 3
Calibration results for the water yield, water purification, and sediment retention models.

Indicator	Gauge site	Source	Unit	Observation	Estimation	Diff., %
Flow rate	Pocatello	NWIS[a]	m^3/year	2.1E+08	2.1E+08	0.1
TP export	Siphon road	IDEQ[b]	kg/year	4.5E+05	4.4E+05	−2.1
TN export	Lower Marsh Creek	IDEQ	kg/year	1.4E+05	1.3E+05	−2.7
TSS export	Siphon road	IDEQ	tons/year	3.2E+04	3.3E+04	1.4

[a] NWIS: National Water Information System.
[b] IDEQ, an integrated report of total maximum daily load (TMDL) from Idaho Department of Environmental Quality (IDEQ, 2010).

and 60% decrease of CRP in the two scenarios would contribute to 20% and 43% increase of TSS export, respectively. However, the model results suggest conservation could counteract some effects of climate change. In the CRP Reboost scenario, the TSS export would decrease by 9% instead of the 11% increase. The contribution of climate change would slightly decline from 11% to 9%, with the offsetting effect of CRP trend by 18%. In addition to the CRP Reboost scenario, the CRP Reboost+Riparian scenario would further reduce the TSS export by 8% due to riparian protection, with the total reduction by 17% and the relative contribution of CRP increasing from 18% to 26%.

By mapping of the spatial distribution of TSS export, the Benchmark scenario (Fig. 9) suggests that the high TSS export subcatchments are likely to be associated with drainage areas with intensive agricultural practices, especially the subcatchments along Marsh Creek (Hopkins et al., 2011; Marcarelli et al., 2009). With regards to climate change, the TSS export in the first quartile is lower than the second and third quartile because the rainfall erosivity is relatively low in the climate model. For the CRP scenarios, a big difference in TSS export might be manifested by choosing either more CRP or less CRP enrollment scenarios in the future. The TSS export in the subcatchments along Marsh Creek would potentially increase by at least 13% under the CRP Decline scenario, while it might decrease by at least 17% under the CRP Reboost +Riparian scenario (Fig. 9 (b) vs. (h)).

Table 4
InVEST freshwater model outputs for the Portneuf River catchment.

Scenario	Realized water yield, mm[a]			TP export, kg/year		
Benchmark	35.8			4.63E+04		
Percent change, 2000 to 2050[b]						
	Total	Climate	CRP	Total	Climate	CRP
CRP Loss	−103%	−56%	−47%	11%	0%	11%
CRP Decline	−80%	−56%	−24%	5%	0%	5%
CRP Baseline	−56%	−56%	0%	0%	0%	0%
CRP Reboost	−33%	−56%	23%	−7%	0%	−7%
CRP Reboost+Riparian	−26%	−56%	30%	−10%	0%	−10%
Scenario	TN export, kg/year			TSS export, tons/year		
Benchmark	4.60E+05			3.03E+04		
Percent change, 2000 to 2050						
	Total	Climate	CRP	Total	Climate	CRP
CRP Loss	16%	0%	16%	59%	16%	43%
CRP Decline	8%	0%	8%	34%	14%	20%
CRP Baseline	0%	0%	0%	11%	11%	0%
CRP Reboost	−8%	0%	−8%	−9%	9%	−18%
CRP Reboost+Riparian	−11%	0%	−11%	−17%	9%	−26%

[a] The water yield, without considering the consumptive use, is 119.7 mm in 2000 and 99.6 mm in 2050.
[b] Since this study focuses on the conservation side of influence, the InVEST outputs from 20 climate models centered on 2050 were averaged for each CRP scenario and compared with the Benchmark scenario centered on 2000.

3.4. In-stream indicator

In addition to the catchment-level and subcatchment-level results, we also estimated the annual fluxes of water, nutrients, and suspended sediment at the site level to understand the impacts on the Portneuf River (Table 5). The Pocatello and Siphon Road sites for which we estimated correspond to physical gauge sites near the outlet of the river (Fig. 1). The site-level response of flow rate is less radical than the catchment-level one because the subcatchments downstream of the Pocatello site, which are mainly occupied by croplands, were not included in estimation. As shown in the CRP Baseline scenario, the flow rate at the Pocatello site might decrease by 37% due largely to climate change. The flow rate would be ~68% less under the CRP Loss scenario, possibly causing the Portneuf River to go completely dry near the city of Pocatello (Fig. 1). In contrast, the water scarcity might be relieved by 15% and 18% under the CRP Reboost and CRP Reboost+Riparian scenarios.

The site-level responses for TP, TN, and TSS export are similar to the responses at the catchment level. However, water scarcity would be a multiplier factor if the nutrient and suspended sediment export change is considered with the flow rate change. Taking the CRP Baseline

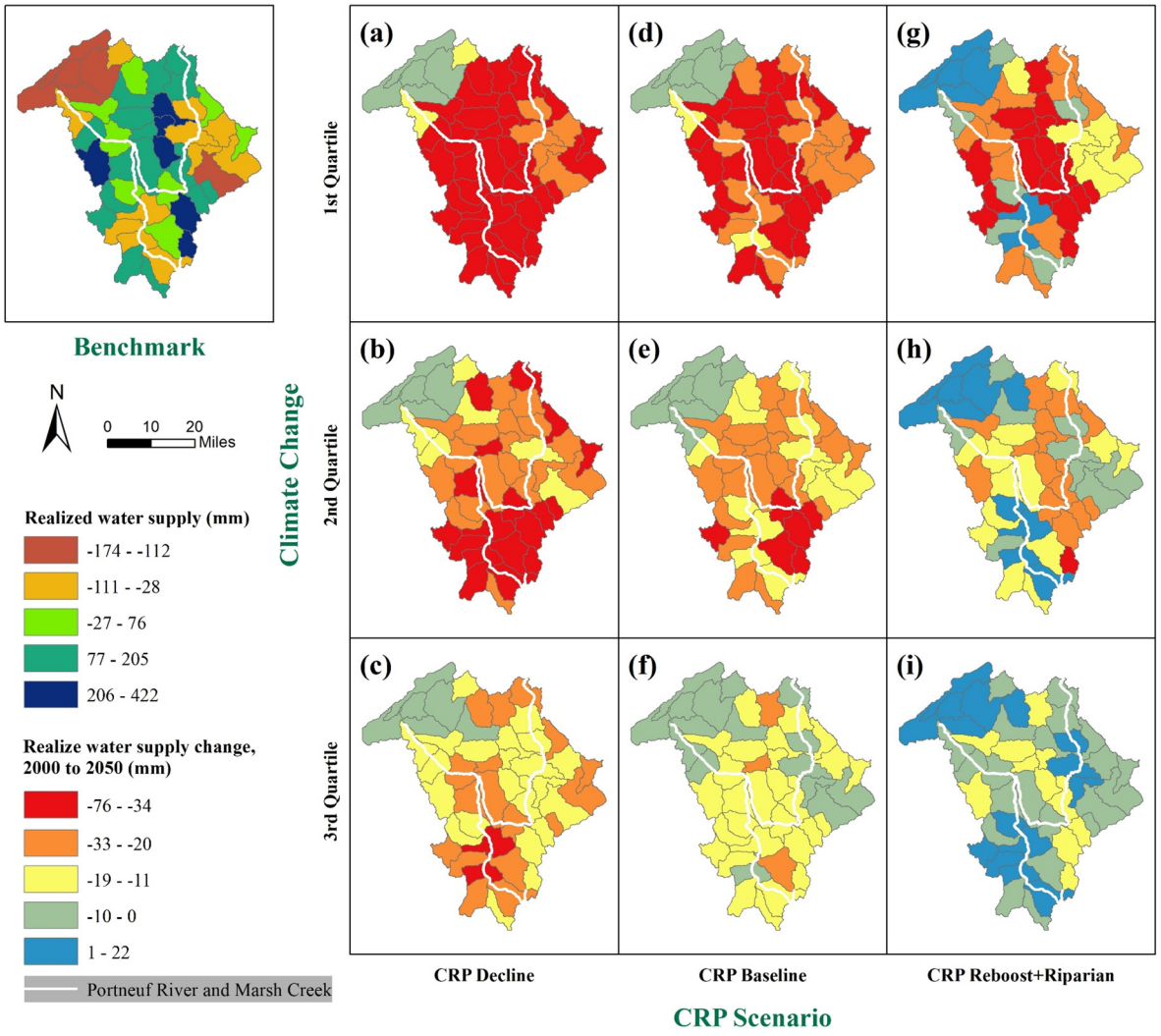

Fig. 6. Realized water supply and its change for selected scenarios. Note: Due to the limited space, 20 climate models are represented by the first, second, and third quartiles of their subcatchment outputs. The CRP Decline and Reboost+Riparian scenarios are selected to represent the greatest effects of land conversions.

scenario as an example, the concentrations of TN and TP in streams would increase by 60% if the flow rate decreases by 37%, even though there is no change in the mass export. Therefore, water quality, measured by nutrient concentration and turbidity as exports in the Portneuf River, might be degraded or improved when the flow rate change is also considered.

To better understand freshwater ES variation in Portneuf River and facilitate potential communication with stakeholders, we further estimated the annual trend of flow rate and TSS export in response to dry and wet climate conditions (Fig. 10). Though the precipitation in the catchment would likely to increase in the catchment, the increase of potential evapotranspiration would potentially exceed the increase of precipitation due to warming climate. As a result, the flow rate is possible to decrease substantially, leading to a drier river in years around 2040 and 2065. Another likely consequence of more precipitation in the catchment is larger rainfall erosivity, and thus more TSS export and river with turbidity. Based on the average value in the years 1986–2015, the largest increase of precipitation in the years 2036–2065 is 21% and TSS export will increase by 35%, while the decrease of precipitation by 3% will lead to the decrease of TSS by 5%. The next section will present the overall assessment of variation and uncertainty in the modeling.

3.5. Sensitivity analysis

There are two main sources of uncertainty that could be concluded in this assessment by InVEST (Gaber et al., 2009): the input data uncertainty and the parameterization uncertainty. The uncertainty of input data focuses on the climate and land use data, and the parameterization uncertainty focuses on the calibrated parameters.

As shown in Table 6, eight input factors were selected in sensitivity analysis of the realized water yield model, with five focusing on the calibrated parameters, i.e., the water consumption coefficient of croplands (WC_{crp}); the vegetation evapotranspiration coefficient (Kc_x) of croplands, rangelands, and forest (x equals "*for*", "*rng*", or "*crp*"); and the seasonal factor (Z), and three focusing on the input data, i.e., precipitation (*Pr*), evapotranspiration (*Eto*), and land use data (*luc*) (Hamel and Guswa, 2015; Redhead et al., 2016; Sánchez-Canales et al., 2012). There are three implications based on the ranking and values of μ^*. First, the climate factors, *Pr* (ranked 1st) and *Eto* (3rd), are among the most influential inputs determining the model output. Second, among the three dominant land use types, the model output is the most sensitive to the coefficient of rangelands (2nd), followed by forest (6th) and croplands (8th). Third, besides *Pr*, *Eto*, and Kc_{rng}, the other five factors are relatively low in μ^* values, indicating that the model output is relatively stable in the tested range. Based on the σ values, little coupling

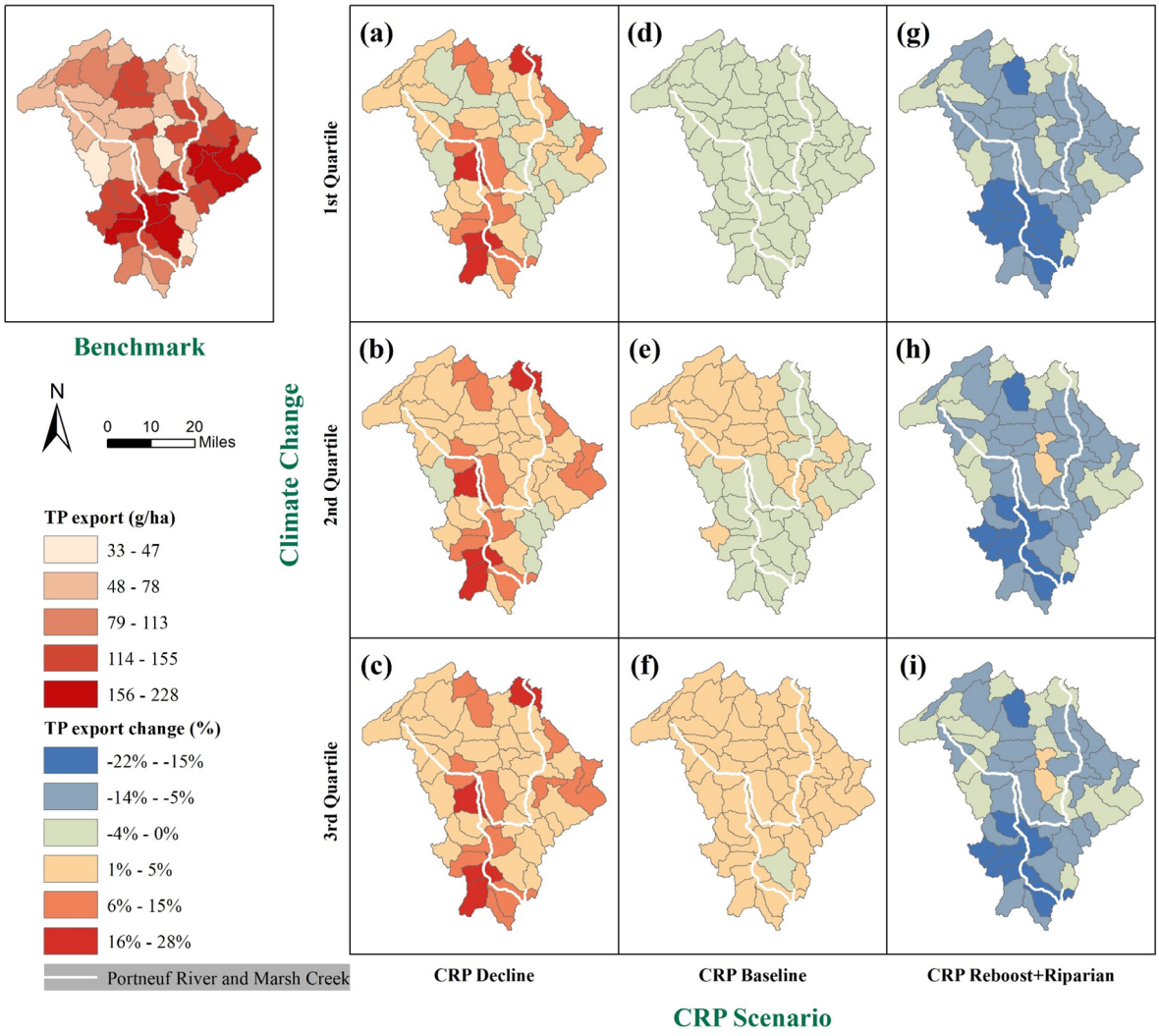

Fig. 7. Total phosphorus (TP) export and its change for selected scenarios.

effects, namely, the nonlinear effects and/or interaction with other factors, are observed for each factor (Morris, 1991).

For the nutrient retention model, we evaluated the sensitivity to the nutrient load coefficient ($load_x$) and the maximum retention efficiency (eff_x) of forest, rangelands, and croplands, as well as the change of CRP enrollment (luc) (Redhead et al., 2018). For the TP export, the load coefficient and the retention efficiency of rangelands are the most influential inputs, followed by croplands (Table 6). The model is sensitive to the coefficients of rangelands and croplands because the two types of land cover occupy a significant proportion of the catchment area and have relatively high coefficient values. The coefficients of rangelands and croplands also have relatively high σ values, indicating the existence of nonlinear effects and/or interaction with other factors. However, the coefficients of forest and land use change are less influential to the TP export, of which the coupling effects are also weak. For the TN export, the load coefficient of cropland is the most influential factor for TN export followed by rangelands and forest, while the retention efficiency of the three land use types and the CRP enrollment change are less influential., The coupling effect of factors in the TN export model is relatively weak, of which the highest is the σ value of merely 0.06 for the land use change factor. Compared with TP export, the uncertainty in TN export is mainly decided by $load_x$ but not both of $load_x$ and eff_x. The difference might be attributed to the fact that the magnitude of the input space for $load_x$ is relatively larger than eff_x in TP model.

Nine inputs were selected for sensitivity analysis of the sediment retention model (Hamel et al., 2015; Sánchez-Canales et al., 2015). The first six inputs are the support practice factor (P_x) and the management factor (C_x) of forest, rangelands, and croplands. The later three inputs are rainfall erosivity (R), soil erodibility (K), and CRP enrollment change (luc). The P and C factor of croplands are the most influential among the nine factors, followed by the C factor of rangeland, soil erodibility, and rainfall erosivity. The model sensitivity to the other four factors, P_{for}, P_{rng}, C_{for}, and luc, is relatively low. The results imply that croplands, which accounts for a significant proportion of the catchment and requires considerable maintenance and management, is the most influential land use type in the sediment retention model. The σ value of factors also shows that the couple effect of the P and C factor of croplands is relatively strong, indicating the existence of nonlinear effects and/or interaction with other factors and the necessity to carefully design and calibrate the coefficients related to the croplands.

4. Discussion

4.1. Freshwater ecosystem services and mitigating degradation

In this study, we assessed how freshwater ES would likely respond to climate change and land conservation in a semiarid catchment. Unlike the previous assessments focusing on climate change alone or

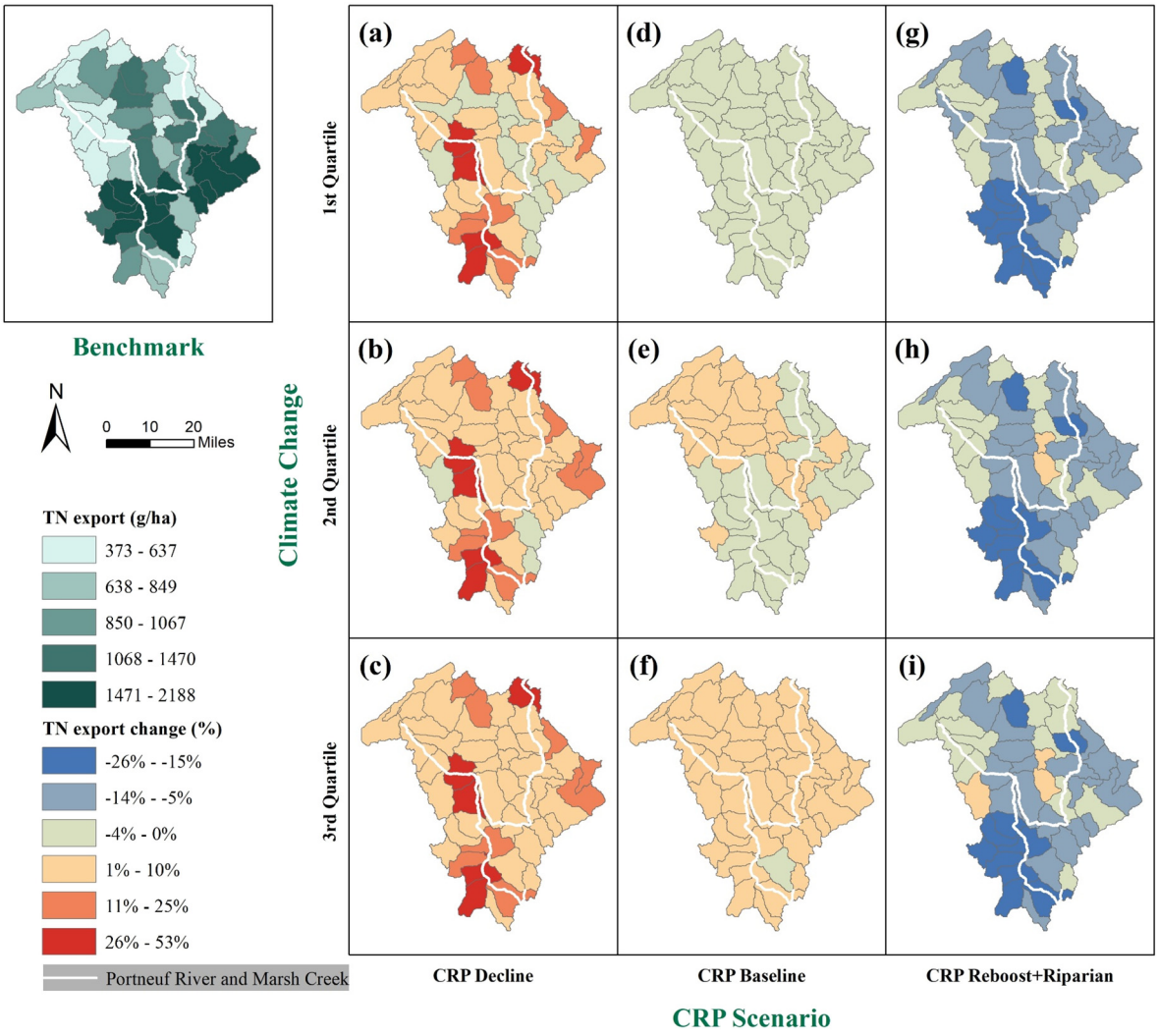

Fig. 8. Total nitrogen (TN) export and its change for selected scenarios.

climate change and land use changes like urbanization (Bangash et al., 2013; Hoyer and Chang, 2014; Terrado et al., 2014), this study emphasizes the potential mitigation effects of conservation through more CRP enrollment. This study complements the previous studies by deepening the scenario building approach without increasing the difficulty to interpret the results and inform current land management and agricultural conservation policies. Though we tested more than 100 scenarios, the results were averaged along the climate change dimension to highlight the impact on freshwater services under alternative CRP scenarios. By applying the InVEST modeling approach, the presentation of the spatially explicit outputs provides information about the expectation and the spatial variation of responses to climate change, together with the representative CRP scenarios. The empirics show that environmental benefits from conservation are clear and provide guiding information to land management and conservation planning for the Portneuf River and other catchments facing severe freshwater ES challenges, especially under the context of global environmental change and declining institutional interests on conservation like the CRP cap drop in the USA since the 2014 farm bill.

We comprehensively disentangled the relative contribution of climate change and agricultural land conservation by applying the RESTREND method, which to date has been used only for the water yield modeling (Pan et al., 2015). The results show that promoting 29% of current CRP enrollments and implementing 30 m of riparian buffers within the catchment could counteract the water quantity and quality issues, which concurs with a large body of riparian literature (Kemp and Dodds, 2001; Larson et al., 2016; Lee et al., 2004), and a recent study that shows riparian protection in arid rangelands has played a strong role in protecting stream ES (Larson et al., 2018). Notably, the declining CRP enrollments would likely exacerbate the relative contribution of climate change, indicated by the 11% increase of TSS export due to climate change in the CRP Baseline scenario and 16% of increase in the CRP Loss scenario. On the other hand, improved conservation practices may help mitigate the adverse effects of climate change, as suggested by reductions in its relative effect on TSS export to 9% in the CRP Reboost+Riparian scenario. The alternative CRP scenarios indicate that increasing conservation efforts would relieve water scarcity and reduce nutrient and sediment exports due to changing climate conditions such as increasing runoff and evapotranspiration.

4.2. Implications for land management and conservation planning

Our results from the InVEST modeling have several implications for conservation resource allocation and land use management at the local and global level. First, conservation efforts should be devoted to solving the water scarcity problem because water scarcity is a multiplier factor for water quality, as discussed in Section 3.4. The drainage areas along Marsh Creek should be the priority given their sensitivity to climate and land use changes, and because this tributary provides large contributions of water to the Portneuf River. As indicated by the

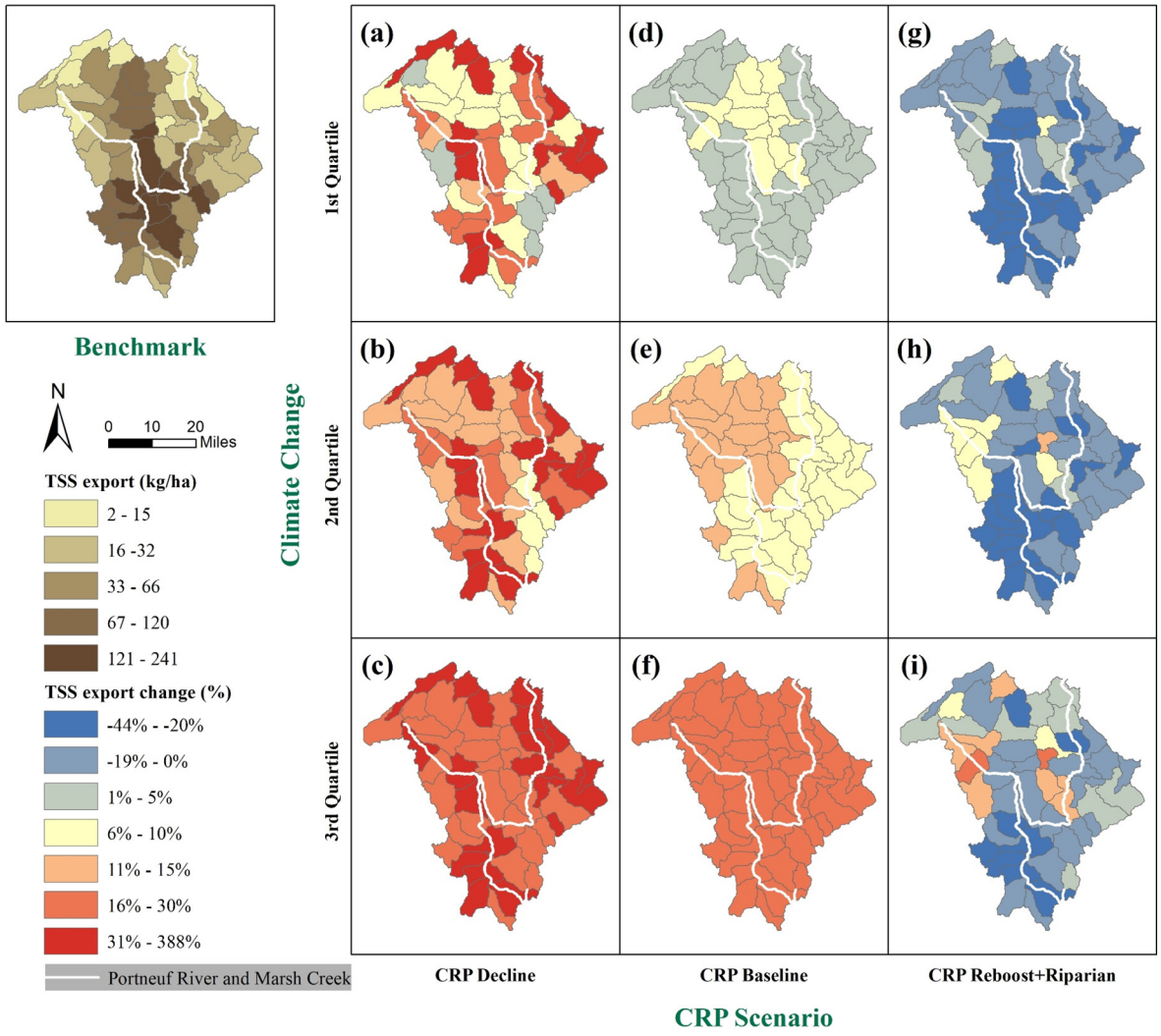

Fig. 9. Total suspended sediment (TSS) export and its change for selected scenarios.

comparison between the CRP Reboost and CRP Reboost+Riparian scenarios in the results section, 30 m riparian buffers would likely provide several improvements in addition to CRP conservation for the Portneuf River and the people living in the catchment, including 7% reservation of current water supply, 3% reduction of TP and TN export, and 8% less of TSS export. We hope this information can further inform the Total Maximum Daily Load plans (IDEQ, 2010) and the restoration of freshwater ES for the Portneuf River (http://river.pocatello.us/).

Table 5
Estimated indicator at gauge sites.

Scenario	Flow rate at Pocatello site, ft^3/s	TP export at Siphon Road site, lb/day	TN export at Siphon Road site, lb/day[a]	TSS export at Siphon Road site, tons/day
Benchmark	229.69	236.68	2364.3	74.36
Percent change, 2000 to 2050				
CRP Loss	−68%	12%	17%	60%
CRP Decline	−53%	5%	8%	33%
CRP Baseline	−37%	0%	0%	11%
CRP Reboost	−22%	−7%	−9%	−10%
CRP Reboost+Riparian	−19%	−10%	−11%	−18%

[a] Though Lower Marsh Creek site was used in calibration, Siphon Road site was estimated to capture the overall impact.

Second, though agricultural production could possibly be a potential threat to freshwater ES in the Portneuf River catchment, it could also present an opportunity to achieve environmentally friendly and sustainable development, in which the technology and management factor could play a major role in mitigating environmental degradation in addition to conservation. Consumptive use, mainly in croplands, occupies a large portion in water yield reduction (Eq. (A.1)). Currently, irrigation withdrawal in the catchment constitutes up to 95% of the total water supply (about 92.8 million gallons per day). Our models show that with climate change, the flow rate could be reduced drastically in the Portneuf River, and so the people of Pocatello, the broader Portneuf basin, and the Shoshone-Bannock Tribes would need to cope with more evident challenges due to potential degradation of ES provided by the river. Adoption of advanced irrigation technology would possibly relieve the water scarcity problem and the extreme case of stream dry-up by withdrawing and consuming less water on per unit cropland. As shown in Table 7, the consumption coefficient and the withdrawal coefficient have declined from 1990 to 1995 and from 2005 to 2010 in the Portneuf River catchment and in Bannock County where Marsh Creek is located. On the other hand, present inefficiencies in agricultural water use are an important source of baseflow in the Portneuf River and other similar rivers (Baker et al., 2014; Marcarelli et al., 2010), and in this region water demand by users with junior water rights may consume any water savings achieved via efficiencies.

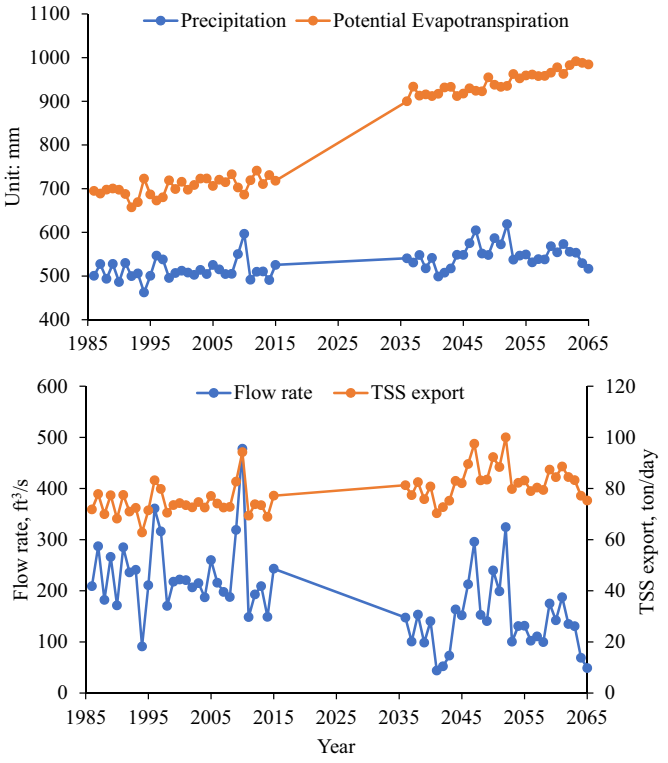

Fig. 10. Annual trend of freshwater ecosystem services in the Portneuf River.

Third, the assessment also provides some insights relevant to land use planning and catchment management. After the record-high 1963–1964 floods, a flood management plan channelized the river in concrete through the city of Pocatello. The 1.6 miles of concrete channel provides effective flood control but causes problems such as degradation of aesthetic value and less favored habitat for wildlife and fish due to removed vegetation, levee maintenance, directly dumped storm water and waste, and low dissolved oxygen (Castro et al., 2018; Quintas-Soriano et al., 2018). The future scenarios we present here regarding water scarcity and concentrating pollutants in the river may further justify the consideration of channel removal and replacement to riparian protection, which would benefit both the city of Pocatello and the catchment.

4.3. Uncertainty in the ES assessment by InVEST

To quantify uncertainty, we utilized both the scenario analysis and sensitivity analysis. Scenario analysis is a powerful way to deal with uncertainty and serves the purpose of being hypothesis driven, tractable, and easily understood by stakeholders (Bryant and Lempert, 2010). The depth of scenario building in this study to the two dimensions of climate change (20 climate models in total) and land use change induced by land conservation (five CRP scenarios covering the exploitation and conservation directions) is not common in other studies that have utilized InVEST. The potential ES change trajectories and the spatially explicit outputs in alternative scenarios not only illuminate the outcomes of different land management practices but also imply the potential uncertainty regarding the input data of climate and land use.

In sensitivity analysis, the enhanced Morris method was used to explore the global sensitivity across the model's input space. The results indicate that the water yield model is sensitive to precipitation and evapotranspiration (Hamel and Guswa, 2015; Sánchez-Canales et al., 2012), and rainfall erosivity is influential for the sediment retention model (Hamel et al., 2015; Sánchez-Canales et al., 2015). The parameters of major land use types, i.e., croplands and rangelands, are influential to model outputs of water provision, water purification, and sediment retention (Hamel and Guswa, 2015; Redhead et al., 2018; Sánchez-Canales et al., 2015). However, the model output is not sensitive to the CRP enrollment factor, which is contrary to the results of ES change analysis. The insensitivity to land use change, i.e., CRP enrollment change in

Table 6
Sensitivity analysis of factors in the InVEST models.

Factor	Description	Range	μ^*	σ
Water yield model				
WC_{crp}	Water consumption coefficient of croplands, m^3 per pixel	[270, 330]	0.093	0.001
Z	Seasonal factor	[7, 10]	0.106	0.022
Kc_{for}	Vegetation evapotranspiration coefficient of forest	[0.70, 1.10]	0.101	0.011
Kc_{rng}	Vegetation evapotranspiration coefficient of rangelands	[0.60, 0.90]	0.241	0.045
Kc_{crp}	Vegetation evapotranspiration coefficient of croplands	[0.75, 0.95]	0.027	0.011
Pr	Precipitation[a]	[−20%, 20%]	0.440	0.031
ETo	Evapotranspiration[a]	[−20%, 20%]	0.207	0.033
luc	CRP enrollment	[−30%, 30%]	0.105	0.012
Nutrient retention model[b]				
$load_{for}$	nutrient load of forest	[0.05, 0.50] ([1.50, 3.50])	0.066 (0.100)	0.019 (0.009)
$load_{rng}$	nutrient load of rangelands	[0.20, 0.85] ([0.30, 2.00])	0.381 (0.192)	0.116 (0.009)
$load_{crp}$	nutrient load of croplands	[0.50, 2.50] ([5.00, 20.00])	0.275 (0.526)	0.111 (0.047)
eff_{for}	maximum retention efficiency of forest	[0.60, 0.80] ([0.20, 0.35])	0.046 (0.030)	0.038 (0.011)
eff_{rng}	maximum retention efficiency of rangelands	[0.25, 0.75] ([0.05, 0.25])	0.317 (0.053)	0.182 (0.024)
eff_{crp}	maximum retention efficiency of croplands	[0.25, 0.75] ([0.01, 0.10])	0.238 (0.022)	0.142 (0.013)
luc	CRP enrollment	[−30%, 30%]	0.046 (0.083)	0.047 (0.061)
Sediment retention model				
P_{for}	support practice factor of forest	[0.20.0.90]	0.058	0.049
P_{rng}	support practice factor of rangelands	[0.20, 0.90]	0.087	0.066
P_{crp}	support practice factor of croplands	[0.20, 0.90]	0.295	0.209
C_{for}	management factor of forest	[0.001, 0.010]	0.118	0.085
C_{rng}	management factor of rangelands	[0.001, 0.010]	0.182	0.095
C_{crp}	management factor of croplands	[0.100, 0.300]	0.260	0.187
R	rainfall erosivity factor	[−20%, 20%]	0.165	0.078
K	soil erodibility factor	[−20%, 20%]	0.167	0.114
luc	CRP enrollment	[−30%, 30%]	0.100	0.076

[a] The climate inputs, Pr and ETo, were changed uniformly across the landscape.
[b] For comparison, the values for TP are listed with TN values in parentheses.

Table 7
Irrigation activity in Portneuf River catchment and Bannock County.

	Irrigation withdrawals, Mgal/day	Consumptive use, Mgal/day	Irrigation acres, in thousands	Withdrawal coefficient, Mgal/(day·10^3 acres)	Consumption coefficient Mgal/(day·10^3 acres)
Portneuf River catchment[a]					
1985	288.79	72.08	81.50	3.54	0.88
1990	238.59	77.54	42.82	5.57	1.81
1995	285.60	92.82	54.47	5.24	1.70
Bannock county					
1985	282.94	65.42	71.00	3.99	0.92
1990	196.18	63.76	31.05	6.32	2.05
1995	263.17	85.53	45.40	5.80	1.88
2000	352.95	–	45.82	7.70	–
2005	369.64	–	46.16	8.01	–
2010	134.41	–	34.19	3.93	–

[a] After 1995, only withdrawals were reported by National Water-Use Science Project and statistics at the catchment scale has been no longer available.

this study, is due to the spatial configuration of land use/land cover that mainly affects freshwater ES by the biophysical coefficients of given land use type (Redhead et al., 2018).

This study could support decision making and communication with stakeholders, but we acknowledge several limitations in the assessment procedures. For the climate inputs, the error was reduced globally by averaging 20 CMIP5 models (Rupp et al., 2013). Yet, more variation and uncertainty are embedded at the local scale, which could lead to either underestimates or overestimates of the subcatchment responses (Fig. B.1). The LULC data are not perfectly accurate either. The error in LULC data, especially for the grassland category, could also be a source of uncertainty in assessment (Hou et al., 2013; Hoyer and Chang, 2014). Under climate change, retreat of grasslands and rangelands might be possible with drier conditions. But within this study, we assumed that the land use change in the region is mainly led by changes regarding the CRP enrollment. In parameterization, all the parameters were calibrated globally, so the goodness of fit at the catchment level does not necessarily mean there is no bias at the subcatchment level (Layhee et al., 2015). Limited by the current framework, InVEST modeling of nutrient retention and export is weakly related to climate conditions by runoff potential index, which could be improved in the future update of the tool. In sensitivity analysis, land use parameters were not evaluated based on the two-digit NLCD code but more general categories of forest, rangelands, and croplands. Integrating models in series or in parallel, with data of higher temporal and spatial resolution and lower uncertainty, and comparing their performance and sensitivity are desirable in the future research (Hallouin et al., 2018; Johnston et al., 2011; Sharps et al., 2017).

5. Conclusions

In this study, we used a spatially explicit modeling tool, InVEST, to investigate the intertwined impacts from climate change and croplands conservation to the freshwater ES in a semiarid catchment (i.e., the Portneuf River basin in Idaho, USA). The results suggest that potential degradation of ES like water supply, water purification, and sediment retention is possible due largely to the negative impacts of climate change on the hydrologic cycle in the catchment. The results indicate that land conservation practices, such as the CRP and riparian protection, could offset climate change in their relative contributions to ES change. Alternative CRP scenarios suggest that decreasing CRP enrollment might exacerbate the negative consequences to the riverine ecosystem, while increasing CRP enrollment would mitigate the degradation and diminish the contribution of climate change. Our analysis has potential implications for policy making, catchment management, and stakeholder engagement to improve the ES provided by this and other similar rivers draining semiarid agricultural watersheds. Although we modeled results specifically for the Portneuf River catchment, the implications likely transfer to other catchments that would be influenced by climate change, changing enrollment in CRP, and riparian protection legislation and practice. The scenario analysis and sensitivity analysis in the study facilitate a more nuanced understanding of drivers in ES change and provide insights into ES assessment.

Conflict of interest

The authors declare no potential conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article report the InVEST modeling methods, performance of CMIP5 models, sensitivity analysis method, calibrated InVEST parameters and example of local uncertainties. Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.09.260.

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